

Effect of micro-environmental factors on natural regeneration of *Sal* (*Shorea robusta*)

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Abstract: Micro-environmental factors viz., soil moisture and light intensity are important factors that affect natural regeneration in forests. These factors vary spatially depending on the overhead canopy density of the forest. The present study focused on studying the effect of variation of soil moisture and light intensity on natural regeneration of *sal* species (*Shorea robusta*) under different micro-environments due to overhead canopy of varying forest density. Experimental plots of 40m× 40m size were laid under different overhead canopy densities in a small *sal* forested watershed in the foot hills of Himalayas in Nainital District of Uttarakhand State, India. The plots were monitored on a long term basis for soil moisture at multi depths, light intensity and natural regeneration of *sal*. The results of the study revealed that the natural regeneration was highest under C1 (up to-0.30) canopy followed by C2 (0.30–0.50), and C3 (0.50–0.70) canopies. The C3 canopy showed the dying back of *sal* shoots over 4 years of study. The highest R^2 value of linear regression between incremental score of plot regeneration and average soil moisture content was obtained as 0.156 for average soil moisture content during non-monsoon months at 100 cm depth. The R^2 value between incremental score of plot regeneration and annual average light intensity was obtained as 0.688 which indicated that the regeneration is largely dependent on the light intensity conditions during the year. The multiple linear regression analysis between the incremental score of regeneration and the average light intensity and average soil moisture content revealed that that about 80% of variation in regeneration is explained by both the factors.

Key words: Natural regeneration, *sal*, canopy density, soil moisture, light intensity

Introduction

Shorea robusta or *sal* is an important timber-yielding plant known for its heavy, hard and tough wood, and is one of the major forest types in South Asia. Its geographic range extends from the southern slopes and lower foothills of the Himalayas to plains, river slopes and valleys in Nepal, Bangladesh, India, Bhutan and South China, between 75° and 95° E longitude and 20° to 32° N latitude (Gautam & Devoe 2006; Sapkota 2009). *Sal* forests cover about 0.12 million ha in Bangladesh (Alam et al., 2008), 1.4 million ha in Nepal (Rautiainen 1999) and 10.57 million ha in India (Rathore 2000). In India, *sal* forest is widely distributed in tropical regions and covers about 13.3% of the total forest area in the country. In the Himalayan foothill belt, it extends up to the Assam valley (including Meghalaya and Tripura) in the east to foothills of north-west Bengal, Uttar Pradesh, Uttarakhand, and Kangra region of Himachal Pradesh.

Natural regeneration is the inherent ability of a tree species to reproduce itself and is a direct indicator of health of a forest ecosystem. Though many known and unknown causative factors affect the process of natural regeneration, the major factors include (Singh et al. 1987): climate (humidity, temperature, light intensity, span of light receiving hours, precipitation and wind); soil (depth, aeration, moisture level, nutrients and erosion); seed (sensitivity, output and dispersal); and biotic conditions (wildlife, forest fire, and overgrazing) etc.. Over a small area, majority of these factors, however, remain more or less uniform but the natural regeneration in *sal* has been found to vary under different overhead canopy densities. Since the micro-environmental factors such as soil moisture and light intensity vary under different canopy densities (Jetten 1994; Rose 2000; Dam, 2001; Hutchinson et al. 2005; Vandenberghe et al. 2006), there is a need to study the natural regeneration in relation to these factors at a small watershed level. The present study was, therefore, carried out in a small watershed of *sal* forest with the major objective of assessing the effect of variation of soil moisture and light intensity on natural regeneration of *sal*.

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Several studies on regeneration of *sal* have been carried out in the past and the factors like biotic (grazing and fire), seeding, canopy density, plant communities, competition of weeds, climate, nutrient requirements, growth of seedling along shade and moisture gradients, root growth and its penetrability have been studied (Champion, 1933; Davis 1948; Pande 1956; Soni 1961; Seth 1961; Rao and Singh 1984; Saxena and Singh 1984; Singh and Singh, 1984; Tewari 1982; Upreti et al. 1985). However, the studies on natural regeneration in relation to the factors such as soil moisture and light intensity are rare (Dabral et al. 1980). Hole (1914, 1921) and Boyce & Bakshi (1959) observed that poor soil aeration and inadequate moisture are mainly responsible for unsatisfactory *sal* regeneration. Seth and Bhatnagar (1960) found positive correlation between soil moisture content and good regeneration. Srivastava (1972) observed that the maximum height growth, foliage development and uptake of potassium and phosphorus of *sal* was at 37% moisture, i.e. at 85% of water holding capacity, but it did not withstand water logging condition because of bad soil aeration.

Gautam et al. (2007) reported that the correlation of *sal* with soil moisture was positive ($r = 0.127$ and $p < 0.01$) at seedling stage, positive but not significant at sapling stage and negative ($r = -0.102$ and $p < 0.05$) in the mature stage. Chauhan et al. (2008) carried out a multiple regression between seedling density of *sal* and six soil parameters (soil moisture, soil organic carbon, pH, nitrogen, phosphorous and potassium) and reported the value of coefficient of determination (R^2) as 0.042 and 0.222 in natural and planted forest, respectively. Sapkota (2009) found that seedling regeneration of *sal* differed significantly between the gap and intact vegetation environments. The seedling density was higher in the gaps than in the intact vegetation. Generally, canopy gaps always have higher light intensities at the soil surface and hence often higher soil temperatures, than areas with closed vegetation (Denslow, Aaron & Sanford, 1998). Pokhriyal et al. (2010) compared two watersheds for *sal* regeneration and found that the regeneration was better in Phakot than Pathri Rao watershed. It was concluded that Pathri Rao watershed comes under a protected area and lopping was not allowed within the national park, and thus the forest having good canopy cover might have affected the survival of seedlings under good tree canopy due to the absence of light. In the present study, the soil moisture and light intensity were considered for their correlation with natural regeneration of *sal* as all other weather and biotic factors can be assumed to remain uniform over a small area of the size of the study watershed.

Materials and methods

Study area

A *sal* forested watershed of about 16.40 ha, located between latitudes 29°20'29" to 29°20' 57"N and longitudes 79°18'26" to 79°18'37"E, was selected in Musabangar village of Kaladhungi Tehsil in Nainital district, Uttarakhand, India. The study watershed was fenced by a barbed wire to protect it from grazing by

villagers' animals and browsing by wild animals like pigs, deer and porcupines which cause a great disturbance to the natural regeneration. The normal annual rainfall of Nainital district is about 1 528 mm, of which about 80% occur in monsoon months of July to September. The watershed drains into a small stream named Garuni. The entire study watershed is covered under *sal* forest of varying canopy density. The elevation in the watershed varies from 562 m at the upstream to 526 m at the outlet. The slope of the watershed though varies from flat to about 72%, the major area (approx. 80%) falls under slope range of 5% to 25%. Soil samples were collected from 27 locations in the watershed and analyzed for grain size distribution in the laboratory using mechanical sieve shakers and laser based particle size analyzer. The analysis revealed that the watershed chiefly consists of silt loam with medium to coarse gravel. The canopy density survey of the watershed was conducted by the Department of Forests of Uttarakhand State under three canopy density classes of C1, C2 and C3, representing respectively the areas where canopy density has reduced to (0–0.30), (0.30–0.50), and (0.50–0.70).

Experimental layout and data collection

In order to study the regeneration response of *sal* to varying soil moisture storage and light intensity under different canopy densities, a series of twenty seven experimental plots of 40m × 40m size was demarcated in the watershed under three density classes of C1, C2 and C3, with nine experimental plots in each canopy (Fig. 1). The watershed was instrumented for measuring rainfall, soil moisture and light intensity. The instruments included an ordinary rain gauge (ORG) in combination with a tipping bucket rain gauge and soil moisture sensors of 'Water Mark' make at 25, 50 and 100 cm depths in each of the experimental plots to monitor the soil water potential at different depths. A Lux meter was used to record the light intensity.

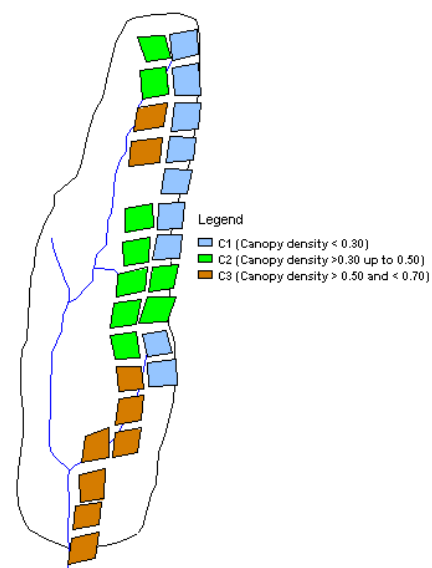


Fig. 1: Layout of experimental plots

An intensive data collection programme was initiated in the watershed towards the end of the year 2005. The soil water po-

tential in all the sensors was monitored at weekly intervals and converted to volumetric soil moisture content using the soil-moisture retention curves developed for respective sites and depths. Few of these sensors were either damaged by wild pigs

or malfunctioned after some time and therefore these were discarded for further observations. The temporal variation of soil moisture along with corresponding rainfall was plotted for all the sites as illustrated in Fig. 2 for one of the sites.

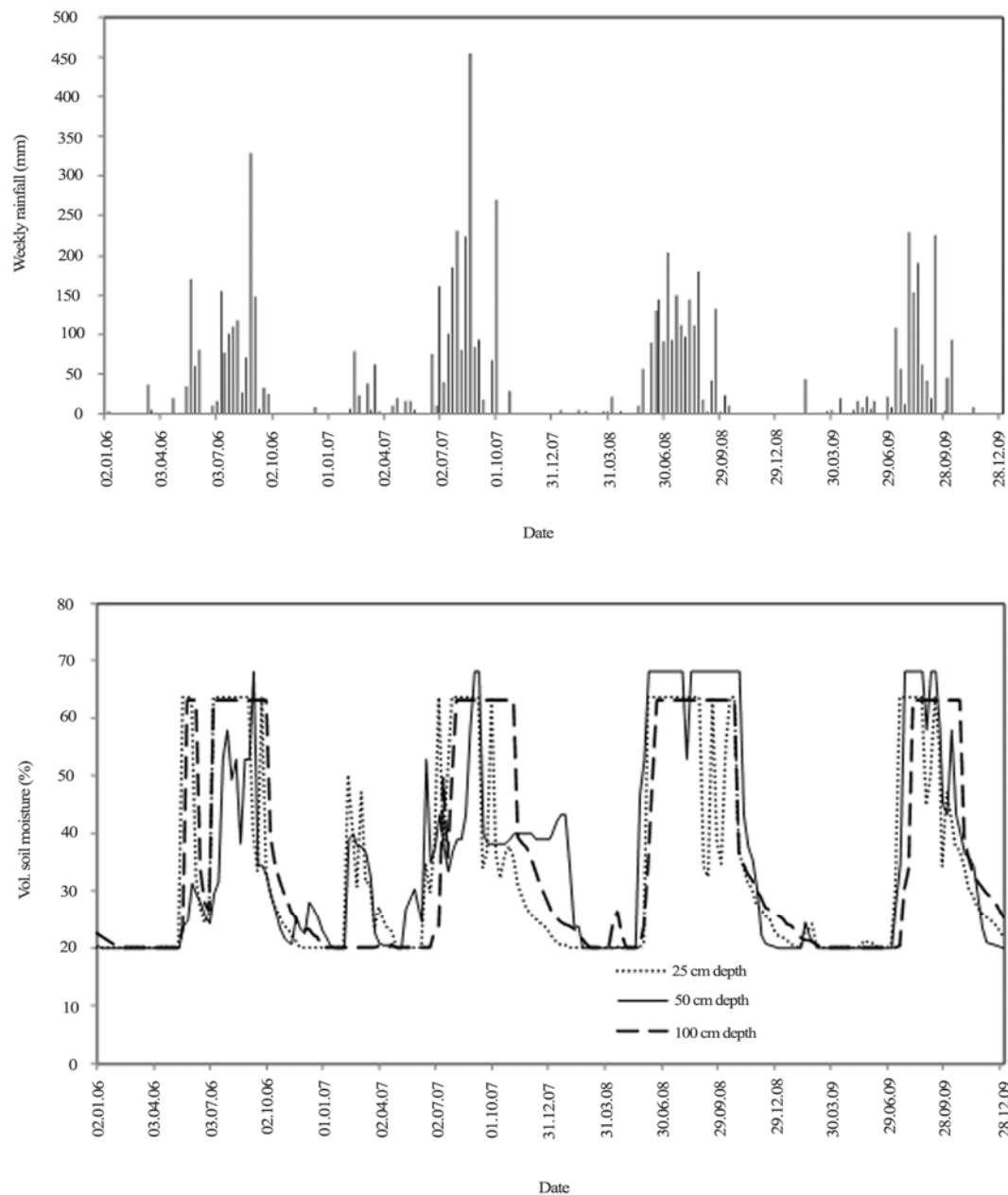


Fig. 2 Illustration of temporal variation of soil moisture storage in a sample plot

The soil moisture variation was found to respond well to the rainfall and the evapotranspiration. The soil moisture values at 25 cm depth were found to increase quickly with occurrence of rainfall and also depleted at a faster rate as compared to those at 50 cm and 100 cm depths. It is obvious that a longer time is required for percolation of water to greater depths. Also, the evaporation from soil mostly takes place up to 20–30 cm depth and therefore the soil moisture is depleted quickly in this layer. Though the soil moisture at all three depths is observed at high-

est level during rainy months of July to September (monsoon season), it sustains for longer duration at 100 cm depth as there is no evaporation from this depth. The soil moisture starts depleting during dry months (non-monsoon season) and reaches its lowest value at all three depths. It was observed from the temporal plots of soil moisture that winter rains of low magnitude and prolonged duration caused rise in soil moisture generally up to 50 cm depth but the isolated rainfalls of high magnitude were found to contribute to the soil moisture up to 100 cm depth. The effect

of isolated storms at 25 and 50 cm depth, however, might not have been captured as the observations were taken at weekly intervals and soil moisture in upper layers must have depleted due to evaporation.

The monthly average soil moisture at 25, 50 and 100 cm depth in each experimental plot was also computed by averaging the weekly values of four years of observation (i.e. Jan. 2006 to Dec. 2010). The monthly average soil moisture values were found to vary from plot to plot and also among plots under same canopy density. Therefore, canopy wise monthly average soil moisture under the canopy densities of C1, C2 and C3 was calculated by taking arithmetic mean of the monthly average soil moisture values of all the plots lying under respective canopy densities.

The observations on light intensity were taken using Lux meter (in Lux units) at fortnightly interval in all the twenty seven plots. The observations were taken at breast height at two representative locations in each plot. The average value of both the readings was taken as the plot's light intensity. The average incidence of light intensity under C1, C2 and C3 canopy densities was computed by averaging the light intensity of plots under each canopy density. The variation of light intensity under each of the three canopy densities is plotted in Fig. 3. It can be observed that, in general, the incidence of light intensity decreases as the canopy gets thicker. During monsoon season the light intensity is generally lower than that during non-monsoon season in all three canopies. On cloudy days, the light intensity reduces drastically and remains more or less same in all the canopy densities.

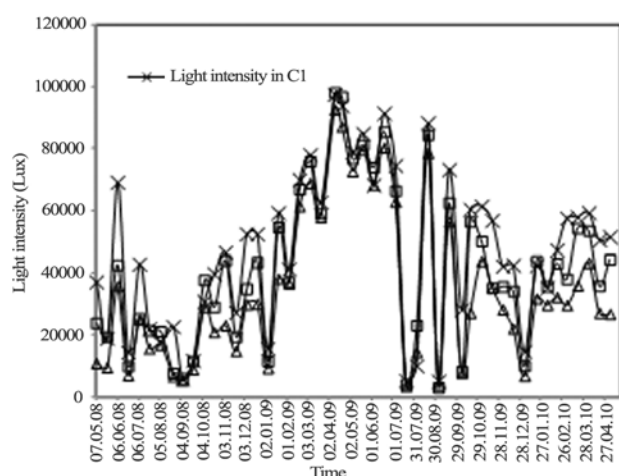


Fig. 3: Variation of light intensity in different canopy densities

The regeneration survey for *sal* in the experimental plots was conducted by the Department of Forests during the months of January/February in the years 2006, 2007, 2008, 2009, and 2010. For the survey purpose, a standard procedure followed by the Department of Forests was adopted. The regenerated plants/shoots were classified into five categories depending on their height/health and a weight was assigned to the plant as given in Table 1.

Table 1. Categories of regeneration survey

Categories	Description	Weight
E	Established shoot of <i>sal</i> which has attained a height of 2.50 m and a diameter of 10 cm	5
W	Woody shoot of <i>sal</i> which has not attained the height of 'E' but would establish being healthy with good growth	4
U+	Whippy shoot (' <i>Lachila</i> ') with a height of more than 50 cm but is not yet fully established	2
S+	Sub-whippy shoot (' <i>Chhoti Lachili</i> ') with a height of less than 50 cm	0.5
R	A new shoot germinated in the year of counting	0

The year wise regeneration score of individual experimental plot was computed as the sum of the product of number of plants in various categories and their respective weights. The incremental score over a period of four years (i.e. 2006–2010) for each plot was computed as the difference of scores of the years 2010 and 2006. The average incremental regeneration score for the canopy densities of C1, C2 and C3 was calculated by taking mean of the incremental scores of all the plots lying under respective canopy densities. The computed year wise scores and incremental scores of individual plots, and the average incremental scores under C1, C2 and C3 canopies are given in Table 2. It can be observed from Table 2 that the incremental score is highest under C1 canopy followed by C2. The C3 canopy rather shows the dying back with a regeneration score of -167 over 4 years of study.

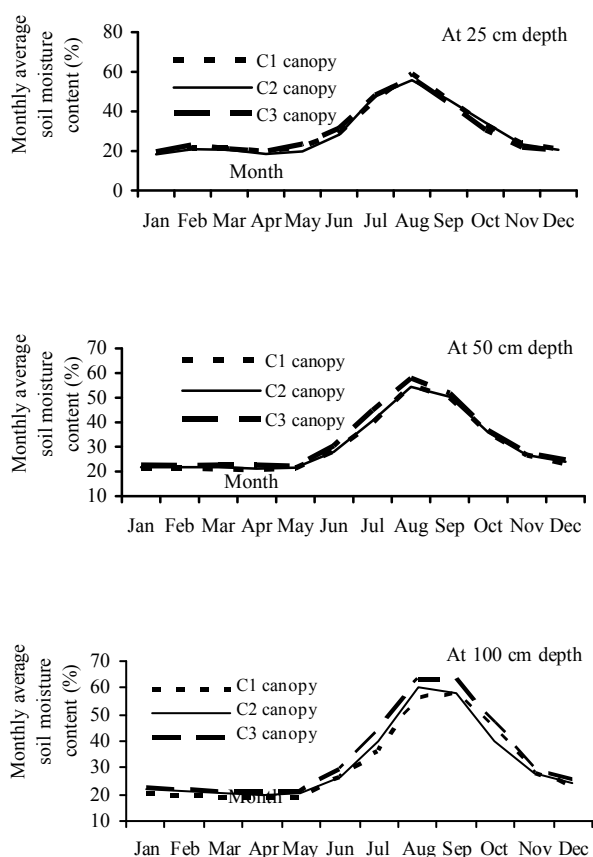
Results and discussion

Variation of Soil Moisture under Different Canopy Densities

The variation in soil moisture regime under three canopy densities was assessed at different depths by plotting the monthly average soil moisture contents under C1, C2 and C3 canopies at 25, 50 and 100 cm depth (Fig. 4). It was observed that the soil moisture regime clearly differs under three canopies at all the depths. The difference in soil moisture is highest at 100 cm depth which decreases with the decrease in depth. At 100 cm depth, the soil moisture is found to be highest under C3 canopy followed by that under C2 and C1 canopies. It is indicative of higher withdrawal of soil moisture under C1 canopy. A trend similar to 100 cm depth is also observed at 50 cm, though the difference in soil moisture levels in C2 and C1 canopies is very small. At 25 cm depth the trend is not very clear and the soil moisture regime in three canopies is found to interchange with time. This is probably due to the fact that the depletion of soil moisture at 25 cm depth is affected more by evaporation than transpiration. It is also observed that the replenishment and depletion of soil moisture due to rainfall and evapo-transpiration respectively is faster at 25 cm depth than at deeper depths.

Table 2. Year wise plot regeneration score, incremental score and average incremental score under C1, C2 and C3 canopy densities

Canopy density	Plot no.	Year wise plot score of regeneration					Incremental score during 2006 - 2010
		2006	2007	2008	2009	2010	
C1	1	10338	10833	11661	11676	11907	1569
	2	7448	7921	8222	8281	8444	996
	3	13885	14248	15829	15840	16329	2444
	4	16862	17185	17791	17799	17938	1076
	5	6985	7435	7554	7607	7798	813
	6	9558	9663	10413	10455	10673	1115
Average incremental plot score over 4 years							1335
C2	1	2526	2585	2797	2805	2963	437
	2	8345	8448	8970	8984	9086	741
	3	6099	6252	6944	6978	7089	990
	4	4473	4554	4704	4790	4942	469
	5	6785	6890	7296	7312	7429	644
	6	5792	5895	6223	6265	6386	594
Average incremental plot score over 4 years							646
C3	1	5905	6068	4903	4907	4986	-919
	2	3178	3380	3264	3268	3332	154
	3	4710	4971	5100	5106	5168	458
	4	3888	4093	4019	4024	4117	229
	5	1987	2022	1927	1930	1970	-17
	6	8802	8898	7746	7750	7894	-908
Average incremental plot score over 4 years							-167

**Fig. 4** Monthly average soil moisture content under three canopy densities at 25, 50, and 100 cm depths

Effect of soil moisture on regeneration

The regeneration in *sal* is affected by dying back. Therefore to minimize its effect in any individual year, the incremental score for each plot was computed over 4 years as presented in Table 2. In order to examine the bearing of soil moisture on regeneration, the average soil moisture values over 4 years (corresponding to the period of incremental score) were determined at each of the three depths for the periods: (1) January to December, (2) November to June, and (3) January to June. The period of January–December included the periods of highest moisture (July to October), lowest moisture (January to June) and moderate moisture (November to December). Since the soil moisture during July to October should pose no scarcity for regeneration, this period was excluded from the periods at sl no. (2). The period at S.No. (3) represented only dry period.

The average soil moisture content of the experimental plots during each of the above period at all three depths were plotted against average incremental scores of respective plots and a straight best fit line was drawn, as depicted in Fig. 5 for 100 cm depth. The results of the regression analysis revealed that a very poor but positive correlation existed between regeneration and soil moisture at 25 cm depth during the period (Jan. to Dec.) and almost no correlation existed during the periods (Nov. to June) and (Jan. to June). The regeneration was found to be positively correlated with soil moisture both at 50 and 100 cm depths. The value of R^2 was obtained as 0.076, 0.103, and 0.088 for soil moisture at 50 cm depth during the periods (Jan. to Dec.), (Nov. to June), and (Jan. to June) respectively; and 0.121, 0.156, and 0.153 for soil moisture at 100 cm depth during respectively pe-

riods. These R^2 values are found in line with the values reported by others, for example, Gautam et al. (2007) reported $r = 0.127$ between *sal* seedling and soil moisture; Chauhan et al. (2008) reported multiple regression R^2 between *sal* seedling density and six soil parameters (soil moisture, soil organic carbon, pH, nitrogen, phosphorous and potassium) as 0.042 in natural forests, and 0.222 in planted forests. These R^2 values, however, indicate that soil moisture could explain only little variation in regeneration and other factors might play a major role. In the present study, the R^2 values as 0.156 and 0.153 further indicate that the regeneration is governed by the soil moisture content of dry months especially at 100 cm depth than that at 50 and 25 cm depth. These results can be further supported by the Fig. 4 which shows the lowest levels of monthly average soil moisture under C1 canopy at 100 cm depth. As the incremental regeneration score is maximum under C1 canopy (Table 2), higher withdrawal of soil moisture takes place from 100 cm depth under C1 canopy.

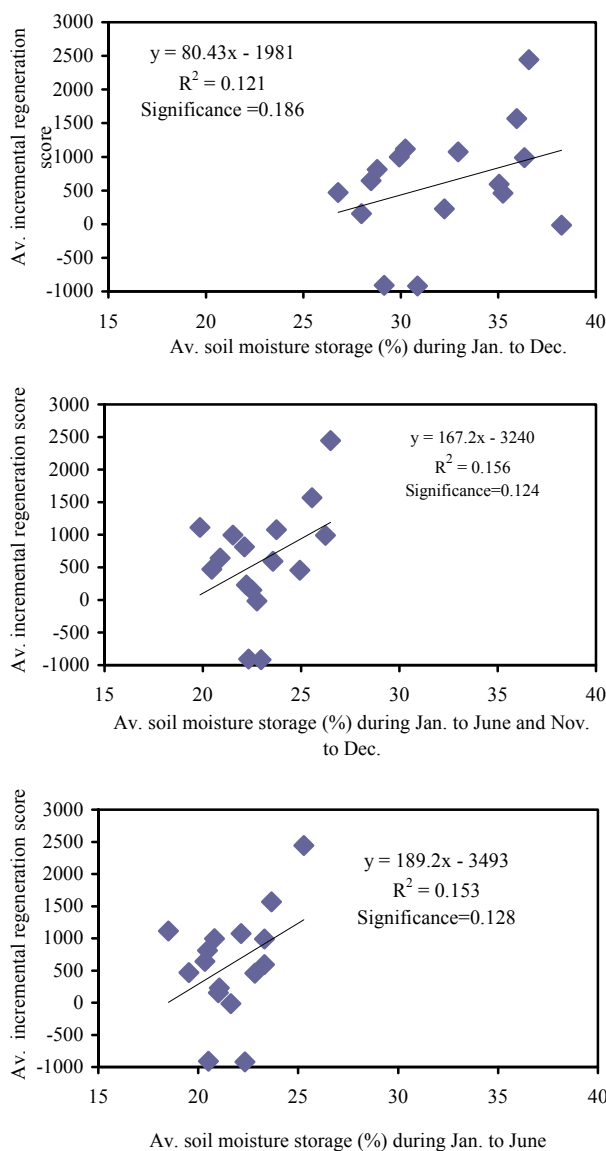


Fig. 5 Plot of average incremental regeneration score and average soil moisture content at 100 cm depth

Effect of light intensity on regeneration

For assessment of effect of light intensity on regeneration, the annual average light intensity in each plot was computed by averaging the fortnightly observations over the study duration. The annual average light intensity of all the plots was plotted against the incremental regeneration score of respective plots and a straight best fit line was drawn (Fig. 6). The regression analysis yielded the following equation.

$$y = 0.091x - 3132; R^2 = 0.688 \quad (1)$$

The R^2 value of 0.688 indicated that the regeneration is quite dependent on the light intensity conditions during the year. This inference, in general, is in agreement with the findings of Sapkota (2009), Pokhriyal et al. (2010) and others. The rates of emergence and survival of seedlings increase with increases in the number and size of canopy gaps as the canopy gaps always have higher light intensities at the soil surface, and hence often higher soil temperatures (Bullock, 2000; Hutchinson et al. 2005; Vandenberghe et al. 2006).

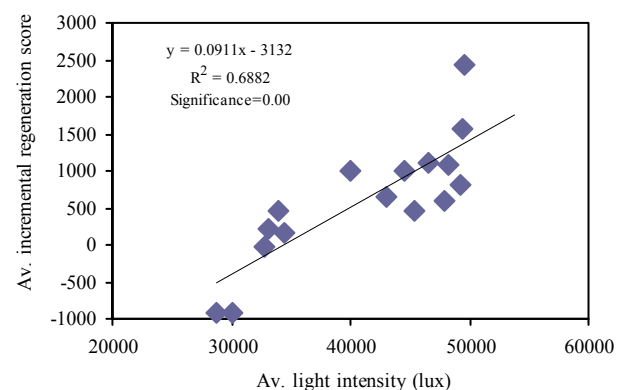


Fig. 6 Plot of average incremental regeneration score and average light intensity

Combined Effect of Soil Moisture and Light Intensity on Regeneration

In order to analyze the variation of regeneration due to combined effect of soil moisture and light intensity, a multiple linear regression analysis was carried out between the average incremental regeneration score and average light intensity and average soil moisture content of the period (Nov. to June) at 100 cm depth using the SPSS (ver 16.0) software. The R^2 value of 0.798 (Table 3) indicated that about 80% of variation in regeneration is explained by the light intensity and soil moisture content of the non-monsoon months at 100 cm depth. The student's 't' test indicated that the values of both light intensity and soil moisture content were significant at ($p < 0.01$) and ($p < 0.025$) respectively.

It is to be pointed out here that the above results are based on

the data collected from a small forested watershed in which anthropogenic disturbances are minimized by fencing of the area. Except the micro-environmental factors namely soil moisture and penetration of light intensity which were found to vary with

canopy density, all other climatic, soil and biotic factors are more or less uniform across the watershed. It is because of this reason that the soil moisture and light intensity together could explain as high as 80% variation in natural regeneration.

Table 3. Statistical summary of multiple regression analysis between the average incremental regeneration score and average light intensity and average soil moisture content of the period (Jan. to June and Nov. to Dec.) at 100 cm depth

Variables	Regression coefficients	't' test parameters		R	R ²	Adjusted R ²	Std. error of estimate
		't' value	Significance (p)				
Intercept (constant)	-6248.905						
soil moisture content	140.584	2.665	0.019	0.894	0.798	0.767	404.003
Light intensity	0.088	6.431	0.000				

Conclusions

Based on the results and analyses carried out in the study, the following conclusions were drawn.

(1) The natural regeneration was found highest under C1 (up to-0.30) canopy followed by C2 (0.30–0.50), and C3 (0.50–0.70) canopies. The C3 canopy rather showed the dying back with a regeneration score of -167 over 4 years of study.

(2) The analysis of monthly average soil moisture content under C1, C2 and C3 canopies revealed that the difference in soil moisture among three canopies was highest at 100 cm depth which decreased with the decrease in depth. At 100 cm depth, the soil moisture was found to be highest under C3 canopy followed by that under C2 and C1 canopies. It is indicative of higher withdrawal of soil moisture under C1 canopy.

(3) The linear relationship between incremental score of plot regeneration (over 4 years) and average soil moisture content yielded a highest R² value of 0.156 for the average soil moisture content during the period (November to June). No correlation was found with soil moisture at 25 cm depth. This indicated that the regeneration is governed by the soil moisture content of dry months especially at 50 to 100 cm depth than that at 25 cm depth.

(4) The incidence of light intensity was highest under C1 canopy that decreased with the increase in canopy density. The R² value of linear regression between incremental score of plot regeneration (over 4 years) and annual average light intensity was obtained as 0.688 which indicated that the regeneration is largely dependent on the light intensity conditions during the year.

(5) The multiple linear regression between the incremental score of plot regeneration and average light intensity and average soil moisture content of the period (Nov. to June) at 100 cm depth indicated that about 80% of variation in regeneration is explained by both the factors.

The results of the study amply indicated that the soil moisture and light intensity are crucial parameters for management of natural regeneration in *sal* forests. These results should prove useful in formulating the forest management plans that incorporate the practices to ensure adequate soil moisture and light penetration. Ensuring adequate regeneration and sustained productivity is at the heart of any scientific silvicultural system.

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References

- Alam M, Furukawa Y, Sarker SK, Ahmed R. 2008. Sustainability of sal (*Shorea robusta*) forest in Bangladesh: past, present and future actions. *International Forestry Review*, **10**: 29–37.
- Boyce JS, Bakshi BK. 1959. Dying of sal. *Indian Forester*, **85**(10): 585–588.
- Bullock JM. 2000. Gaps and seedling colonization. In: M. Fenner (ed.), *Seeds: The ecology of regeneration in plant communities*. 2nd ed., New York: CABI Publishing, pp.375–395.
- Champion HG. 1933. Regeneration and management of sal (*shorea robusta*). *Indian Forest Rec.* (Old series), *Silviculture*, **19**(3). Manager of Publications, Delhi.
- Champion HG, Seth SK. 1968. *A revised survey of the forest types of India*. Delhi: The Manager of Publications.
- Chauhan DS, Dhanai CS, Singh B, Chauhan S, Todaria NP, Khalid MA. 2008. Regeneration and tree diversity in natural and planted forests in a Terai - Bhabhar forest in Katarniaghat Wildlife Sanctuary, India. *Tropical Ecology*, **49**(1): 53–67.
- Dabral BC, Pant SP, Pharasi SC. 1980. Microclimate of a regenerating sal forest in West Dehradun. 2nd *Forestry Conference*, Dehradun.
- Dam OV. 2001. Forest filled with gaps - Effects of gap size on water and nutrient cycling in tropical rain forest. *Tropenbos-Guyana Series 10*, Tropenbos-Guyana Programme, Georgetown, Guyana.
- Davis PW. 1948. Sal natural regeneration in United provinces. *Indian Forester*, **74**(2): 540–552.
- De Jong SM. 1994. Applications of reflective remote sensing for land degradation studies in a Mediterranean Environment. *Ph.D. Thesis*, Utrecht University, The Netherlands. p. 237.
- Denslow JS, Aaron ME, Sanford RE. 1998. Treefall gap size effects on above and below ground processes in a Tropical wet forest. *The J of Ecology*, **86**: 597–609.
- Gautam KH, Devoe NN. 2006. Ecological and anthropogenic niches of sal (*Shorea robusta* Gaertn. f.) forest and prospects for multiple-product forest

- management - A review. *Forestry*, **79**: 81–101.
- Gautam MK, Tripathi AK, Manhas RK. 2007. Indicator species for the natural regeneration of *Shorea robusta* Gaertn. f. (sal). *Current Science*, **93**(10): 1359–1361.
- Hole RS. 1914. Ecology of sal (*shorea robusta*). *Indian For Rec*, **5**(4): 87–102.
- Hole RS. 1921. Regeneration of sal (*shorea robusta*) forests – A study in economic ecology. *Ind. Forest Rec.* (Old series), *Silviculture*, **8**(2). Manager of Publications, Delhi.
- Hutchinson TF, Sutherland EK, Yaussy DA. 2005. Effects of repeated prescribed fires on the structure, composition, and regeneration of mixed-Oak forests in Ohio. *Forest Ecology and Management*, **218**: 210–228.
- Jetten VG. 1994. Modelling the effects of logging on the water balance of a tropical rain forest - A study in Guyana. *Ph.D.Thesis*. Dept. Of Physical Geography, University of Utrecht. Tropenbos Series 6, The Tropenbos Foundation, Wageningen, the Netherlands.
- Pande DC. 1956. Natural regeneration of sal in Uttar Pradesh – some recent experimental evidence. *Proc. IX Silvi. Conf.*, Dehradun.
- Pokhriyal P, Uniyal P, Chauhan DS, Todaria NP. 2010. Regeneration status of tree species in forest of Phakot and Pathri Rao watersheds in Garhwal Himalaya. *Current Science*, **98**(2): 171–175.
- Rao PB, Singh SP. 1984. Population dynamics of a foothill sal (*Shorea robusta* Gaertn. F.) forests in Kumaon Himalaya. *Oecol. Plantarum*, **6**: 147–152.
- Rathore CS. 2000. Sal borer problem in Indian sal forests. <http://www.iifm.ac.in/databank/problems/salborer.html> Retrieved on 10th August, 2009.
- Rautiainen O. 1999. Spatial yield model for *Shorea robusta* in Nepal. *Forest Ecology and Management*, **119**: 151–162.
- Rose SA. 2000. Seeds, seedlings and gaps - size matters. A study in the tropical rain forest of Guyana. PhD thesis, Utrecht University. Tropenbos - Guyana Series 9, Tropenbos-Guyana Programme, Georgetown, Guyana.
- Sapkota IP. 2009. Species diversity, regeneration and early growth of sal forests in Nepal: responses to inherent disturbance regimes. Ph.D. Thesis, Swedish University of Agricultural sciences, Alnarp.
- Saxena AK, Singh JS. 1984. Tree population structure of certain Himalayan forest - annotation and implications of concerning future composition. *Vegetation*, **58**: 61–69.
- Seth SK, Bhatnagar HP. 1960. Inter-relation between mineral constituents of foliage, soil properties, site quality and regeneration status in some *Shorea robusta* forests. *Indian Forester*, **86** (10): 590–601.
- Seth SK. 1961. The problem of sal regeneration in Uttar Pradesh. *Proc. VIII Silvi. Conf.*, Dehradun.
- Singh JS, Singh SP. 1984. An integrated ecological studies of eastern Kumaon Himalaya with emphasis on natural resources. Final technical report, DST, Govt. of India, New Delhi.
- Singh AK, Kumra VK, Singh J. 1987. *Forest Resource, Economy and Environment*. New Delhi: Concept Publishing Company.
- Soni RC. 1961. Recent trends in sal natural regeneration techniques with particular reference to B₃ type sal. *Proc. X Silvi. Conf.*, Dehradun.
- Srivastava PBL. 1972. Competitive potential of sal seedlings. *Indian Forester*, **98**(8).
- Tewari JC. 1982. Vegetation analysis along altitudinal gradients around Nainital. *Ph.D. Thesis*, Kumaon University, Nainital.
- Upreti N, Tewari JC, Singh SP. 1985. The Oak forests of the Kumaon Himalaya (India): composition, diversity and regeneration. *Mountain Res. Development*, **5**: 163–174.
- Vandenbergh C, Frelechoux F, Gadallah F, Buttler A. 2006. Competitive effects of herbaceous vegetation on tree seedling emergence, growth and survival: does gap size matter? *Journal of Vegetation Science*, **17**: 481–488.